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Assessment of the CO_2 emission and cost reduction performance of a low-carbon-emission concrete mix design using an optimal mix design system

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ABSTRACT

The production of concrete, a major construction material, emits a large amount of CO_2 from the material production stage, such as in the production of cement, aggregates, and admixtures, to the manufacturing stage, and it is expected that a reduction of CO_2 emission will be required. Accordingly, a study on the assessment of the appropriate amount of CO_2 emission in the concrete production is necessary. As a result, in environmentally developed countries, studies have been conducted on the production of low-CO_2-emitting concrete, such as a low-carbon concrete procurement system, but studies on this topic have been insufficient in Korea. Therefore, this study evaluated the appropriateness and the reduction performance of the low-carbon-emission concrete (LCEC) mix design system and the deduced mix design results using an evolutionary algorithm (EA), the optimal mix design method, which minimizes the CO_2 emission of the concrete mix design. This study established a mix design database from approximately 800 concrete mix designs with different strengths and used an EA to deduce the optimal mix design. When deducing the optimal mix design, we considered design variables, object functions, and constraint functions to develop the algorithm. Then, the appropriateness and reliability of the mix design deduced from the optimal LCEC mix design system, which in turn was developed by using the above algorithm, were evaluated. Additionally, case studies of current structures in Korea were divided into the actual concrete mix designs and the deduced optimal mix designs, which were compared to analyze the CO_2 emissions. According to the case study of the concrete mix design deduced from this assessment system, the CO_2 emissions of the optimal mix design compared to the actual mix design were reduced by 4 and 7% for 24 and 30 MPa concrete, respectively.

Contents

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1. Introduction

1.1. Research background purpose

The amount of energy consumption and CO_2 emission from the Korean construction industry accounts for 23% of the total industry energy consumption and 40% of the total CO_2 emission. As one can tell from the greenhouse gas reduction goal of 26.9% below business-as-usual (BAU) by 2020[1], the construction industry is recognized as an anti-environment industry for mass consumption/mass waste, and thus, it is necessary to make efforts to turn it to an environment-friendly industry. In particular, the production of concrete, a major construction material, emits a large amount of CO_2 from the material production stage, such as in the production of cement, aggregates, and admixtures, to the manufacturing stage, and it is expected that a reduction of CO_2 emission will be required. Accordingly, a study on the assessment of the appropriate amount of CO_2 emission in the concrete production is necessary. Also, there are researches in progress on concrete mix applying optimal method in concrete industry, but most are regarding target nominal strength estimation and high-strength light-weight concrete mix design, and it is necessary to have a study to draw concrete mix design with reduced carbon emission while satisfying physical properties. Currently, most mix principles regarding required strength, durability, workability, water/cement ratio, coarse aggregate maximum size, slump, and fine aggregate follow the concrete standard specification in case of Korea. Therefore, for the part regarding CO_2 emission which is not included in the standard specification, the current concrete standard specification regulations cannot solve the issue. This is because there are a large number of elements affecting the concrete mix design and also because the physical/chemical constituents of various used materials vary depending on site of origin and composition. The resulting value also has numerous variables, and it is almost impossible to build a mathematical model accurately figuring out the influences by interactions between elements.

Therefore, this study developed 'low-carbon-emission concrete (LCEC) mix design system' applying evolution algorithm(EA) as a design tool to minimize CO_2 emission of concrete mix design reasonably, and the goal is to evaluate CO_2 emission amount, economic value, and reduction performance.

[1] Ministry of Environment, Reduction target of Greenhouse gas in South Korea, 2011

1.2. Research contents and methods

This research constructed database for mix design per concrete strength with total of about 800 in order to find out carbon reduction concrete mix design using optimal design method, using which the sensibility analyses for admixture type and CO_2 emission, admixture mix ratio and CO_2 emission, admixture mix ratio and other material mix amount, and material mix and economic value were conducted. Also, low-carbon-emission concrete mix design process was constructed through evolution algorithm, and by applying that, the low-carbon-emission concrete (LCEC) mix design system was developed. The developed evaluation system was used to compare and analyze CO_2 emission and economic value for the drawn optimal mix design and concrete mix design actually used for current constructed buildings in Korea.

2. Research trends in concrete mix design

The current optimal design algorithm for optimization mainly used two methods: one was a crystallization method and the other was a probability method (evolutionary algorithm, genetic algorithm). Artificial neural networks, which were used to approximate the performance index, were also used. Genetic algorithm that is well known for the advantage of solving the combination problem was used to solve the multi-criteria problem like mix design of concrete. Genetic algorithm(GA) that is well known for the advantage of solving the combination problem was used to solve the multi-criteria problem like mix design of concrete [1,2]. GA, known as a very efficient heuristic algorithm that has been widely used in the various fields of engineering, is based on the mechanism of natural selection and natural genetics [3,4]. The general form of GA is composed of three major operators, i.e., selection, crossover, and mutation throughout optimizing, learning, and searching algorithms [5].

Studies on concrete mix design in Korea are being conducted; they discuss concrete mix design methods and program development using methods such as neural networks and genetic algorithms to satisfy concrete properties and minimize material usage. In general, these studies consider only the improvements on onsite-required performances, such as high-strength and lightweight concrete mix design, water/cement ratio estimation, carbonization depth estimation, quality improvement, and construction time reduction. There has not been sufficient research on the optimal concrete mix design based on environmentally required performance, such as CO_2

emission reduction, and the development of mix design programs has been insufficient.

3. Carbon reduction concrete optimal mix design system using evolution algorithm

3.1. Characteristics of evolution algorithm

An evolution algorithm produces probability variable within a certain range from the first parent individual group which is the initial design variable set of upper 15% near the pre-set objective value to generate the next-generation individual group. Between the parent individual group and next-generation individual group, the variable set nearer to the desired design objective is selected to constitute the next parent individual group. According to the result of such process of variation and reproduction, the optimal design variable value most suited to design objective can be found by adjusting variation range and repeating such process. Also, as the optimal point is searched from multiple points and not a single point, the global solution can be found, parallel computing is available, and the search is executed in a stochastic method based on only function values. Due to such characteristics of evolution algorithm described above, it is very effective when applied to draw carbon reduction concrete mix design. Concrete mix design reacts very sensitively according to the mix amount of each raw material, so the selection of parent individual group mix design is very important. Evolution algorithm constitutes the parent individual group with upper 15% concrete mix design nearest to the target function to draw the optimal mix design, it can fairly reduce errors in next-generation individual group. Also, evolution algorithm uses the design variable of concrete mix design in real number form (kg/m^3) to find the optimal solution, so the calculation speed is relatively fast [6,7].

3.2. Characteristics of low-carbon-emission concrete optimal mix system applying evolution algorithm

Low-carbon-emission concrete optimal mix design system can draw concrete mix design mixed with maximum admixture (BFS/FA) so as to achieve minimum CO_2 emission. This system can drawn the mix design desired by the evaluator through evolution algorithm, which is one of the optimal design method, on the already-constructed mix design DB per concrete strength, and without the basic information of each raw material such as W/B, coarse aggregate size, slump, air content, density, and specific gravity to mix concrete, it can draw optimal mix design by selecting types of admixture and input of concrete strength. To develop this system, concrete mix design data per about 800 nominal strengths investigated from domestic RMC company was constructed into a database. Also, to draw optimal mix design, the constructed database was used for analysis of relationship of admixture type and CO_2 emission, admixture mix ratio and CO_2 emission, admixture mix ratio and other material mix amount, and concrete mix design and economic value to find the target function of optimal mix design.

3.3. Optimal low-carbon-emission mix system development

3.3.1. Mix design database construction for different concrete strength

To establish the database for concrete mix design, normal Portland cement, blast-furnace cement, water, coarse aggregate, fine coarse aggregate, and admixture mix ratios of the 18, 21, 24, 27, 30, 35, 40, 50, and 60 MPa strengths of mix designs, which were supplied to the actual construction site, were provided from 10 domestic ready-mix concrete companies; the size of coarse aggregate, strength, water/cement ratio, and fine coarse aggregate ratio were considered for the concrete properties as shown in Table 1. The approximately 800 mix designs were then categorized by their admixture types and seasons (normal/winter) [8–10].

3.3.2. Concrete mix design sensitivity analysis

1) Admixture types and CO_2 emission amount correlation analysis
The change in the amount of CO_2 emissions was analyzed for different types of admixtures to concrete mix designs of 18, 21, and 24 MPa strength. The average amount of the evaluated CO_2 emissions was calculated by sorting the established database of mix designs of different strengths by admixture types. For all the mix designs of strengths of 18, 21, and 24 MPa, the mix designs with fly ash and blast-furnace slag as admixtures emitted the least CO_2 on average, and the amount of CO_2 emission was reduced by 25, 29, and 26%, respectively, compared with the non-admixture mix designs. In addition, for the same strength mix design, the average CO_2 emission amount was 3% less for the mix design with only fly ash compared with the mix design with only blast-furnace slag, which was attributed to the difference in the CO_2 unit requirement for each material as shown in Table 2 and Figure 1.
2) Admixture addition ratio and CO_2 emission amount correlation analysis
To analyze the correlation of CO_2 emissions with the change in the admixture addition ratio to concrete, established mix designs were grouped by their nominal strengths (18, 21, 24, 27, and 30 MPa), and the average amount of CO_2 emissions was analyzed by changing the blast-furnace slag and flag ash addition ratio. According to the results of the analysis, as the addition ratio of both fly ash and blast-furnace slag increased, the total CO_2 emissions decreased. For mix designs of 18 MPa nominal strength, a mix design with approximately 30% admixtures reduced the CO_2 emission by 27% compared to a mix design with approximately 10% admixtures. Furthermore, for mix designs of a nominal strength of 30 MPa, the maximum difference was 152.7 kg-CO_2/m^3, which was an approximately 36% reduction from the maximum CO_2 emissions. This difference occurred not because of the particular admixtures but because of the reduced amount of cement, which has a relatively high CO_2 emission unit requirement, due to the increased amount of admixture as shown in Table 3 and Figure 2.
3) Admixture addition ratio and other material mix ratio correlation analysis
The total mix designs were divided into six classes, from 0 to 60%, according to the admixture ratio of the concrete, and within the mix design range, the correlations of the mix ratios of other materials (such as aggregate, water, and admixtures) and the maximum/minimum distribution were analyzed as shown in Table 4 and Figure 3. For the correlation analysis, a regression analysis was used to find an equation for each admixture according to the mix ratio. As the admixture ratio was increased, the coarse aggregate varied from a maximum of 997 kg/m^3 to a minimum of 865 kg/m^3, and the fine coarse aggregate varied from a maximum of 982 kg/m^3 to a minimum of 781 kg/m^3. Cement varied from a maximum of 389 kg/m^3 to a minimum of 158 kg/m^3, and water varied from a maximum of 185 kg/m^3 to a minimum of 105 kg/m^3.
4) Admixture concrete mix design and economic value correlation analysis
The economic value was analyzed for 800 concrete mix designs of nominal strengths 18, 21, 24, 27, 30, 35, 40, 45, 50, 60 MPa. The economic value analysis of concrete mix design was applied with Korea's standard value information DB as the product unit cost varies among each raw material manufacturer. For 1m3 concrete mix design analysis, the economic value was most influenced by

mix amount of regular cement and aggregate, and the mixing water and admixture had little influence on economic value. Also, the economic value tended to increase as the strength increased, this was analyzed that regular cement with expensive production unit cost (KRW/kg) had a large influence. For 1m3 concrete mix design, the mix amount of coarse aggregate and fine aggregate was greatest with average of 910 and 870 kg/m^3 but the production unit cost (KRW/kg) was low for each, thus they had less influence than regular cement as shown in Table 5 and Figure 4.

3.3.3. Carbon reduction concrete optimal mix design target function

Based on the result drawn through sensibility analysis above, the carbon reduction concrete optimal mix design target function was set. This is applied to the suitability analysis of offspring individual group drawn through initial individual group and recombination.

M(i) DB min. mix design volume < M(i) Optimal mix design volume < M(i) DB Max. mix design volume
(i=Raw materials of Concrete)
M(i) DB min. ratio < Optimal M(i) Admixture mix ratio < M (i) DB Max. ratio
(i=Concrete compressive strength)
Optimal M(i) CO_2 emission < M(i) DB Min. CO_2 emission
(i=Concrete compressive strength)
M(i) DB Min. Cost < Optimal M(i) Cost < M(i) DB Max. Cost
(i=Concrete compressive strength)

3.4. Optimal low-carbon-emission concrete mix deduction process

1) Assessment information input
In order to draw optimal mix design of carbon reduction concrete through evolution algorithm, the evaluation information is input first of all. Input items include concrete nominal strength, season and admixture type. Upon entering evaluation information, this information is transferred to the already-constructed concrete mix design DB of about 800 as shown in Figure 5.
2) Create initial population
The constructed concrete mix design DB draws concrete mix designs with matching evaluation information (strength/season/admixture type) according to input of evaluation information, which is set as the initial individual group for concrete mix design. This classifies the mix designs with same concrete strength, season, and admixture type across the entire 800 mix designs and applies them to the database for evaluation. Such process is the initial individual group generation process to apply the evolution algorithm.
3) Assess fitness of current population
The suitability evaluation is executed against the initial individual group of concrete mix designs. The suitability evaluation is executed by applying target function drawn through sensibility analysis of admixture type, admixture mix ratio, material mix amount, and economic value and such from concrete mix design DB.
4) Selection
Among each initial individual group concrete mix designs arranged in order, a new concrete mix design group is generated. Also, the upper 15% concrete mix design individual group suited to the target function is selected among the selected concrete mix design group.
5) Crossover
The parent individual group of concrete mix design selected through suitability analysis begins intersection and combination. By executing multi-point intersection and combination and not just a single point intersecting a single part, concrete mix design offspring individual group is generated. The generated concrete mix design offspring individual group executes suitability analysis again. When suitability is not met, it repeats from step 2, and the optimal mix design for carbon reduction concrete is drawn when the suitability is met as shown in Table 6.

3.5. Assessment of appropriateness of the deduced optimal mix design

To test the reliability of the concrete mix design deduced from the LCEC mix design system, we analyzed the mix ratios of an actual mix design with the maximum/minimum amount of admixtures (blast-furnace slag, fly ash) out of the mix designs

Table 2
CO_2 emission and reduction performance for each strength level.

Concrete strength [MPa]	CO_2 emission [kg-CO_2/m^3]				Maximum reduction compared to plain[%]
	Plain	BFS Mixing	FA Mixing	BFS+FA Mixing	
18	295.7	271.3	261.5	220.6	25.4
21	327.8	295.5	285.7	231.2	29.5
24	347.7	316.8	307.1	256.2	26.3

Table 1
Example database of concrete mix design for each strength level.

Season	Strength (MPa)	W/C (%)	S/a (%)	Amount of mixed materials [kg/m^3]							
				G	S	C	B/C	F/A	B/S	W	AE
Winter	21	52.7	49.9	906	893	293	0	33	0	172	1.63
Winter	21	54	49.5	906	881	295	0	0	34	177	1.97
Standard	21	52.4	50.2	919	915	242	0	22	21	164	1.88
Standard	21	54.1	50.4	889	893	291	0	0	40	179	1.66
Standard	24	50.7	49.7	895	875	312	0	35	0	176	1.74
Standard	24	48.3	47.8	925	844	266	0	44	55	176	2.92
Standard	24	45.7	47.5	910	818	188	0	38	151	172	2.26
Winter	24	47.9	49.6	913	883	315	0	35	0	168	2.63
Standard	24	49.5	49.5	889	862	320	0	44	0	180	1.82
Standard	27	45.6	48.9	889	843	166	152	39	0	177	1.94
Standard	27	45	47.7	915	829	355	0	0	27	172	2.29
Winter	27	45.5	47.8	916	832	344	0	38	0	174	2.67
Standard	50	30.5	45	866	728	477	0	64	0	165	7.03
Standard	50	30.3	44	935	732	438	0	0	77	156	4.12

Table 3
Admixture addition ratio and CO_2 emission for each strength level.

Strength [MPa]	CO_2 Emission [kg-CO_2/m^3]					Reduction ratio compared to minimum CO_2 emission[%]
	Admixture mix ratio 10%	Admixture mix ratio 15%	Admixture mix ratio 20%	Admixture mix ratio 25%	Admixture mix ratio 30%	
18	310.7	271.3	–	243.6	226.5	27.1
21	337.8	312.5	–	–	–	7.5
24	347.7	326.8	307.1	–	–	11.7
27	375.5	353.1	–	–	–	5.9
30	434.2	372.04	–	327.4	281.5	35.5

Table 4
Admixture addition ratio and CO_2 emission reduction performance for concrete mix design strength level.

Admixture mix ratio [%]	Amount of mixed materials [kg/m^3]							
	Coarse aggregate		Fine aggregate		Cement		Water	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
0–10	943	911	971	837	326	210	176	122
10–20	997	865	982	781	389	164	185	105
20–30	964	885	938	784	382	158	185	123
30–40	965	911	959	837	366	210	181	122
40–50	969	924	843	810	354	327	164	141
50–60	958	925	857	829	351	322	170	163

Table 5
Economic analysis based on the compressive strength of concrete.

Compressive strength [MPa]	Average economic based on the compressive strength of concrete [Won/m^3]						
	Portland cement	Coarse aggregate	Fine aggregate	Admixture	Water	Chemical admixture	Total
18	22,324	19,925	19,550	960	1810	788	65,357
21	24,072	19,875	18,500	1020	1840	752	66,059
24	28,304	18,925	17,800	1100	1830	610	68,569
27	31,524	18,950	16,900	1420	1850	872	71,516
30	32,452	19,925	18,478	1460	1870	1112	75,297
35	34,376	22,125	15,450	1380	1880	988	76,199
40	36,616	18,255	19,650	2840	2170	1756	81,287
45	38,604	22,925	15,350	2470	2010	1762	83,121
50	41,016	22,175	18,400	2420	1950	1856	87,817
60	50,144	20,375	14,950	3080	1780	2786	93,115

for different strengths actually used on the site and the mix ratio of the deduced optimal mix design, as well as the CO_2 emission amount. The analyzed parameters included the substitution ratio of cement, coarse aggregate, fine coarse aggregate, water, and admixture of concrete of 18, 21, and 24 MPa strength, which are the most frequently used concretes in domestic construction sites; we also analyzed the range of CO_2 emissions. For the analysis methods, the maximum and minimum value of the actual mix designs for different strengths and deduced mix designs for different materials were compared as shown in Table 7 and Figure 6. The results of the analysis show that the deduced mix design values, water/cement ratio, cement amount, coarse aggregates, fine coarse aggregates, and water mix ratios had less than 3% errors on average, indicating that the concrete mix designs by the actual mix design and optimal mix method produced similar results. Furthermore, the CO_2 emission amount was calculated by applying the deduced mix design to the established national LCI unit requirement. For the optimal mix design of a nominal strength of 18 MPa, the CO_2 emission amount was somewhat different from the existing mix design in the database. This was because the amounts of fine coarse aggregate and water were increased, but the amounts of cement, coarse aggregate, and admixtures were decreased. For the 21 MPa mix design, the amounts of fine coarse aggregate and admixtures were decreased, and the mix amounts of cement, coarse aggregate, and water were increased. When the mix designs were analyzed based on their materials, the reduction in CO_2 emission was the greatest when the admixture substitution ratio was increased and both fly ash and blast-furnace slag were used. The admixture mix ratio of the optimal mix design was somewhat lower than the mix designs of nominal strengths of 18, 21, and 24 MPa from the established mix design database, but it was found to be usable as the optimal mix design that satisfied both the strength condition and CO_2 emission, cost condition that were deduced by applying the optimal mix algorithm using the sensitivity analysis.

4. Optimal low-CO_2 emission concrete mix design program development

4.1. Outline

The optimal LCEC mix design program was developed based on Microsoft Visual Basic as shown in Figure 7. It was possible to deduce a concrete mix design that was based on the assessment conditions directly input by an assessor design, established

Table 6
Concrete mix design example deduced from low-carbon-emission concrete optimal mix design system.

Concrete specification	W/B (%)	S/a (%)	Amount of mixed materials [kg/m^3]							
			Cement	Blast furnace cement	Coarse aggregate	Fine aggregate	Fly Ash	Blast furnace slag	Water	Chemical admixture compound
25-18-80	46.9	46.4	330	X	951	894	X	X	156	1.65
	57.9	49.5	199	X	957	946	28	35	111	1.86
	42.9	52.1	162	203	824	876	X	41	132	3.2
	42.7	47.7	184	164	905	807	62	X	105	2.87
25-18-120	46.9	49.3	330	X	953	897	X	X	161	1.65
	58	50	200	X	947	935	35	35	143	1.9
	42.9	52.1	162	203	824	876	X	41	132	3.2
	50.6	48.6	305	X	921	874	27	X	168	0.6
25-18-150	48.3	46.8	296	X	933	808	48	56	170	3.2
	45.4	48.9	223	182	894	834	X	X	184	2.03
	46.3	53.1	272	X	864	621	36	X	169	2.15
25-21-80	46.9	46.5	336	X	951	886	X	X	154	1.65
	44.7	48.8	342	X	911	855	38	X	170	2.85
	42.9	50.2	287	X	865	852	X	123	176	2.05
25-24-120	48.3	46.8	296	X	933	808	48	56	170	3.2
	47.5	46.7	200	202	914	814	X	X	190	1.97
	42.7	47.7	184	164	905	807	62	X	105	2.87
25-24-180	58	52	172	X	997	982	33	17	185	1.24
	45.6	48.9	217	182	894	834	X	X	184	2.03
25-27-210	46	49.3	355	X	839	739	X	X	170	2.9
	49.1	44.5	408	X	871	982	183	71	173	1.2
25-30-150	46.9	49.3	362	X	907	878	X	X	170	1.81
	45.4	48.9	223	182	894	834	X	X	184	2.03
	43.8	44.5	245	X	997	959	87	22	151	3.76
25-30-210	31.3	44.5	408	X	997	759	101	43	158	3,82
	28.9	41.4	219	X	864	621	23	153	160	1.71
25-35-120	46.3	47.2	331	X	914	804	X	X	164	1.91
	47.5	46.7	208	202	914	814	X	X	190	1.97
25-35-180	32.8	49.9	404	X	947	743	65	37	119	2
	44.3	49.2	345	X	849	896	X	X	150	1.97
25-40-150	36.3	45.4	276	X	946	939	65	56	148	3.5
	42.9	52.1	162	203	824	876	30	11	132	3.2
	43.3	49.2	330	X	953	897	X	X	170	1.65
25-45-180	46.8	49.3	362	X	907	878	X	X	170	1.81
	27.5	41.0	218	X	864	621	22.8	X	153	1.71
	31.3	46.9	408	X	936	982	49.9	17	185	0.69
25-50-210	46.6	41.3	336.4	X	942	853	X	X	163	1.79
	32.4	46	396.7	X	878	978	28.8	X	278	2.94
	40.1	46.6	405.5	X	901	924	52	65	120	3
20-60-600	25.7	45.7	426	X	850	716	116	42	160	4.37
	27	42.8	495	X	986	738	68	0	152	9.52

Table 7
Analysis of optimal mix design deduced from LCEC and actual mix design.

Strength	Classification	Amount of mixed materials [kg/m^3]						Substitution ratio [%]	CO_2 emission [kg-CO_2/m^3]
		OPC	G	S	W	AE	FA/BFS		
18	Actual maximum	200	924	906	169	2.04	44/47	31	214.9
	Optimal mix	197	895	942	171	1.41	42/42	29	211.8
	Actual minimum	271	864	621	169	2.16	37/0	12	278.8
21	Actual maximum	224	912	870	176	2.28	49/52	31	238.6
	Optimal mix	229	925	851	178	1.64	47/47	29	243.3
	Minimum	299	905	883	175	1.93	22/0	7	306.7
24	Actual maximum	266	925	844	176	2.92	44/55	27	278.5
	Optimal mix	268	932	872	160	3.05	34/34	20	277.7
	Minimum	331	913	850	173	2.14	25/0	7	336.9

*OPC: Ordinary Portland cement, BFS: ground granulated blast-furnace slag, W: water, AE: chemical admixture compound, SBFS: smart ground granulated blast-furnace slag, G: coarse aggregate, S: fine aggregate.

database, and the optimal algorithm. In addition, the CO_2 emission assessment and cost was classified into an onsite input method, which tested the directly input mix design, and an optimal design method, which tested the optimal mix design deduced from the program [10].

4.2. Mix design information input sheet

4.2.1. Optimal design method

An optimal design method not only deduces the optimal mix design satisfying the strength condition but also calculates the

Table 8
Case evaluation outline.

Location	Bundang-gu, Gyeonggi-do, South Korea
Expenditure	Office
Construction company	P company
Total floor area	462,000 m^2
Building area	16,270 m^2
Plottage	28,192 m^2
Construction period	2009.06–2012.02
Scale	Basement five floor–ground twelve floor

Table 9
Case evaluation and construction evaluation method.

Classification	Actual mix design assessment	Optimal mix design assessment
Quantity	Actual usage[m^3]	
Method	Onsite input method	Optimal design method
Mixing design	Actual mix design	Optimal mix design
Basic unit of CO_2 emission	National LCI DB(South Korea) and Japanese Society of Civil Engineers DB	
Basic unit of cost	South Korea price information DB	
Scope	Concrete raw material manufacture process	
Evaluation contents	CO_2 emission by concrete mix design method CO_2 emission by concrete mix design strength CO_2 emission by concrete mix design materials	

amount of CO_2 emitted and cost by assessing the selected information input of the size of coarse aggregate, nominal strength, slump, admixtures, and season (standard/winter).

4.2.2. Onsite input method

An onsite input method calculated the CO_2 emission and cost of a concrete mix design by applying the CO_2 emission and cost of each material production from the input amount (kg) of each material per 1 m^3 of concrete mix design.

4.2.3. Database construction sheet database

The database of this program was established based on the information on the mix ratios of cement, water, aggregate, and admixtures per 1 m^3 concrete of approximately 800 mix designs of concrete with the nominal strengths of 18, 21, 24, 27, 30, 35, 40, 50, 60, 70, and 80 MPa, which were supplied to the actual construction sites by 10 ready-mix concrete companies in Korea, as well as the basic information of approximately 80 ready-mix concrete companies, such as geographic location and production capacity.

5. Optimal low-carbon-emission concrete mix design application case assessment

5.1. Outline

This case study's target was an office structure of the P construction company; its total ground area was 219,000 m^2, and it had five basement floors and 12 floors above ground as shown in Table 8. The information about the amount of concrete used for the structure was gathered from eight domestic companies, and the data of seven types of concrete standards were collected [11,12]. With these data, the amount of CO_2 emission and cost was evaluated. With the same conditions, the optimal mix design was deduced. And the CO_2 emission and cost assessments were compared and analyzed as shown in Table 11.

5.2. Assessment method

To evaluate the target structure, the CO_2 emission amount and cost per unit cubic meter was calculated for the actual mix design of the standard concrete amount (m^3) and optimal LCEC mix design using the developed assessment program as shown in Table 9. The actual mix design and the optimal mix design were evaluated by the onsite input method and optimal design method, respectively, and the national LCI database was used to determine the CO_2 emission unit requirement [13–15]. For the admixtures without CO_2 emission unit requirements, the database from the Japanese Society of Civil Engineers was used instead as shown in Table 10. Additionally, the concrete mix designs in the case study structure were classified by their methods, strengths, and material properties and evaluated. The assessment of CO_2 emission and cost was divided into a raw material production stage, shipping stage, and manufacturing stage, but for this research, only the raw material production stage was evaluated. This is because this research primarily focused on a comparable analysis of the actual mix design and the optimal mix design; the shipping distance for raw materials and concrete manufacturing equipment affect the assessment of CO_2 emission and cost at the shipping and manufacturing stages and were not relevant to CO_2 emission and cost reduction in this study.

5.3. Assessment results

5.3.1. Comparison and analysis of each concrete mix design method

The concrete used for the target structure was classified by each standard, and the CO_2 emission was quantified. The amounts of CO_2 emitted were 37,379,200 kg from the actual mix design and 35,662,789 kg from the optimal mix design (representing a 4.59% reduction compared to the actual mix design) as shown in Table 12. In particular, compared with the actual mix design, the emission of the optimal mix design was reduced by 4 and 7% for the often-used 25–24 MPa-210 and 25–30 MPa-150, respectively; and for 25–18 MPa-150 and 25–48 MPa-600, the actual and optimal mix designs had similar CO_2 emissions.

5.3.2. Comparison and analysis of each concrete mix design

The maximum, minimum, and average amounts of CO_2 emission and cost from the target structure's actual mix design for different standards were compared with the optimal CO_2 emission and cost of the optimal mix design as shown in Tables 13 and 14. The analysis showed that the amount of CO_2 was reduced by 17, 9, 24, 3, and 1% for 18, 24, 30, 45, and 48 MPa concrete, respectively, compared with the maximum emission of the actual mix. The main factor underlying the reduction was the difference between the amounts of cement, blast-furnace slag, and fly ash of the actual mix and the optimal mix. For 18 MPa concrete, 247 kg of cement and 34 kg of fly ash were mixed for the maximum CO_2 emission actual mix design, and 199 kg of cement, 28 kg of fly ash, and 28 kg of blast-furnace slag were mixed for the optimal mix design. We thought the lesser CO_2 emission unit requirements of fly ash and blast-furnace slag compared with normal Portland cement could have caused the CO_2 emission difference observed. Also, as the result of economic value analysis, it was found to have reduction of about 5, 4, 5, 2, 2%, respectively, for 18, 24, 30, 45, 48 MPa compared to the maximum values for cost of actual mix as shown in Table 15. This is thought to be because the mix was drawn with maximum mix of admixture within the range of satisfying target function and strength for optimal mix design while the costs increased due to the increase in amount of regular cement as the strength increase for actual mix designs.

Table 10
CO_2 Emission and cost of materials.

Material	Basic unit Of CO_2 emission [kg-CO_2/unit]	Basic unit Of cost [Won/unit]
Ordinary Portland cement	National LCI DB(South Korea)	South Korea price information DB
Coarse aggregate	National LCI DB(South Korea)	South Korea price information DB
Fine aggregate	National LCI DB(South Korea)	South Korea price information DB
Blast furnace slag	Japanese Society of Civil Engineers	South Korea price information DB
Fly ash	Japanese Society of Civil Engineers	South Korea price information DB
Water	National LCI DB (South Korea)	South Korea price information DB
Chemical admixture compound	Japanese Society of Civil Engineers	South Korea price information DB

Table 11
Assessment result of CO_2 emissions and cost by each concrete mix design method.

Concrete specification	Using quantity[m^3]	Classification	Company	Amount of mixed materials [kg/m^3]							Admixture substitution ratio [%/m^3]	CO_2 emission [kg-CO_2/m^3]	Cost [Won/m^3]
				C	G	S	F/A	BFS	W	AE			
25-180-80	42.3	Actual mix	A	236	958	909	35	0	161	1.22	13	243.24	70,941
	42.3		B	200	933	930	38	33	167	1.90	26	211.38	68,445
	42.3		C	247	938	959	34	0	151	1.97	12	252.76	72,733
	42.3		D	181	962	931	39	39	158	1.3	30	192.57	67,377
	42.3		E	196	993	910	26	39	157	1.83	25	206.54	68,843
	42.3		F	219	997	903	39	0	159	1.81	15	227.25	70,380
	42.3		G	227	964	902	40	0	164	1.47	15	235.25	70,268
	42.3		H	191	924	982	25	38	146	1.78	25	200.43	68,298
	169.5	Optimal mix		199	957	946	28	35	156	1.65	24	209.05	69,033
	169.5			218	921	971	38	0	157	1.02	15	225.76	69,890
25-180-150	2,088	Actual mix	A	258	887	916	39	0	177	1.34	13	265.81	71,629
	2,088		B	216	885	925	41	35	180	2.04	26	228.04	68,850
	2,088		C	271	864	969	37	0	169	2.16	12	277.32	73,619
	2,088		D	197	895	932	42	42	171	1.41	30	209.24	67,471
	2,088		E	213	965	884	28	42	170	1.98	25	224.19	69,317
	2,088		G	246	950	860	43	0	178	1.59	15	254.82	70,840
	2,088		H	209	891	958	28	42	160	1.95	25	219.19	68,843
	14,618	Optimal mix		272	894	834	36	0	169	2.15	12	278.27	71,064
				202	825	918	43	43	118	2.02	30	207.43	52,963
25-240-210	10,182	Actual mix	A	268	932	872	34	34	160	3.05	20	275.02	73,326
	10,182		B	266	925	835	44	55	176	2.92	27	275.88	72,796
	10,182		C	264	931	896	33	33	160	2.64	20	271.09	73,411
	10,182		D	284	931	896	17	34	160	2.68	15	289.70	74,959
	10,182		E	264	940	896	33	33	160	2.64	20	271.10	73,636
	10,182		F	272	957	902	34	34	160	2.72	20	278.76	75,003
	10,182		H	264	908	875	33	33	160	2.64	20	271.06	72,311
	71,271	Optimal mix		257	933	808	48	56	154	2.85	29	265.02	71,359
25-300-120	17.8	Actual mix	A	334	954	787	59	0	171	2.95	15	337.76	77,733
	17.8		B	296	933	808	56	48	170	3.20	26	303.57	75,177
	17.8		C	334	915	884	46	0	158	2.66	12	335.93	78,735
	17.8		D	260	954	832	56	56	160	1.86	30	268.47	72,782
	17.8		E	282	997	792	38	57	161	2.64	25	289.29	74,707
	17.8		F	324	969	810	57	0	164	2.67	15	327.45	77,597
	17.8		G	369	994	683	65	0	180	3.04	15	371.99	79,581
	17.8		H	275	911	890	37	55	151	2.94	25	281.43	74,263
	71	Optimal mix		272	894	834	48	56	170	2.03	28	280.72	72,410
	71			334	914	884	46	0	158	2.66	12	335.93	78,710
25-300-150	5,842	Actual mix	C	349	880	885	48	0	165	2.78	12	350.89	79,399
	5,842		D	268	929	833	58	58	165	1.92	30	276.68	73,060
	5,842		E	293	981	781	39	59	167	2.74	25	300.44	75,184
	5,842		F	333	957	800	59	0	169	2.74	15	336.54	77,979
	5,842		G	383	969	679	68	0	187	3.16	15	386.04	80,298
	5,842		H	287	895	878	38	57	157	3.06	25	293.53	74,811
	17,526	Optimal mix		321	925	854	34	0	168	2.4	10	324.49	76,847
	17,526			268	929	833	58	58	165	1.92	30	276.68	73,060
25-450-60	1,474	Actual mix	D	387	929	814	49	49	160	4.85	20	388.66	83,709
	1,474		E	387	874	785	49	49	160	6.31	20	388.95	81901
	2,947	Optimal mix		375	918	799	53	36	151	4.99	19	375.93	81,713
25-480-600	1283.7	Actual mix	A	408	911	770	51	51	160	6.12	20	408.89	84,425
	1283.7		D	408	918	786	51	51	160	5.1	20	408.65	84,796
	1283.7		E	408	871	767	51	51	160	6.63	20	408.96	83,452
	3,851	Optimal mix		405	901	924	52	65	153	4.37	20	405.39	87,629

Table 12
Amount of CO_2 emissions and reduction by each concrete mix design method.

Concrete specification	CO_2 emission[kg-CO_2/m^3]		CO_2 emission reduction ration compared to actual mix design[%]
	Actual mix	Optimal mix	
25-18-80	74,978.47	73,701.31	1.70
25-18-150	3,505,414.63	3,475,586.04	0.85
25-24-210	19,677,055.02	18,888,546.89	4.00
25-30-120	44,656.78	43,781.86	1.95
25-30-150	11,356,907.49	10,535,991.50	7.22
25-45-600	1,145,815.56	1,107,869.84	3.31
25-48-600	1,574,422.20	1,561,162.67	0.84
Total	37,379,200.14	35,662,789.31	4.59

Table 13
Amount of cost and reduction by each concrete mix design method.

Concrete specification	Cost[Won/m^3]		Cost reduction ration compared to actual mix design[%]
	Actual mix	Optimal mix	
25-18-80	23,573,155	23,547,448	0.11
25-18-150	1,024,308,072	997,875,843	2.58
25-24-210	5,248,230,444	5,085,827,289	3.09
25-30-120	10,868,235	10,729,520	1.27
25-30-150	2,691,590,502	2,627,270,082	2.38
25-45-600	244,109,140	240,808,211	1.35
25-48-600	324,356,330	318,204,279	1.89
Total	9,567,035,878	9,212,900,172	3.71

Table 14
Amount of CO_2 emissions and reduction by each concrete mix design strength.

Concrete specification	CO_2 emission [kg-CO_2/m^3]				Maximum reduction ration compared to actual mix design[%]
	Actual mix			Optimal mix	
	Maximum	Minimum	Average	Optimal	
25-18-80	251.35	191.13	219.74	207.62	17.40
25-24-210	288.31	269.70	274.70	263.64	8.56
25-30-120	370.53	267.05	313.07	279.39	24.60
25-45-600	387.65	387.28	387.47	374.57	3.37
25-48-600	407.67	407.29	407.50	404.04	0.89

Table 15
Amount of cost and reduction by each concrete mix design strength.

Concrete specification	Cost [Won/m^3]				Maximum reduction ration compared to ;actual mix design[%]
	Actual mix			Optimal mix	
	Maximum	Minimum	Average	Optimal	
25-18-80	72,733	67,377	69,660	69,033	5.08
25-24-210	75,003	72,311	73,634	71,359	4.85
25-30-120	79,581	72,782	76,321	75,560	5.05
25-45-600	83,709	81,901	82,805	81,713	2.38
25-48-600	84,796	83,452	84,224	82,629	2.55

5.3.3. Comparison and analysis of each concrete mix design material

The amounts of CO_2 emission and cost were compared and analyzed for eight different mix designs for the 25–24 MPa-210 concrete used in the target structure as shown in Table 16. The major source of CO_2 emission from 24 MPa concrete was the normal Portland cement for each company. Particularly, D company's actual mix design emitted the maximum amount of CO_2, 289.3 kg-CO_2/m^3, and the optimal mix design emitted the minimum

Table 16
Amount of CO_2 emissions and reduction by each concrete mix design materials.

Materials	CO_2 emission[kg-CO_2/m^3]							
	A company	B company	C company	D company	E company	F company	G company	Optimal
Cement	252.99	251.10	249.22	268.10	249.22	256.77	249.22	242.61
Coarse aggregate	1.30	1.30	1.30	1.30	1.32	1.34	1.27	1.31
Fine aggregate	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.08
Blast furnace slag	1.29	1.67	1.25	0.65	1.25	1.29	1.25	1.82
Fly ash	0.67	1.08	0.65	0.67	0.65	0.67	0.65	1.10
Water	17.92	19.71	17.92	17.92	17.92	17.92	17.92	17.25
Chemical admixture compound	0.76	0.73	0.66	0.67	0.66	0.68	0.66	0.71
Total	275.02	275.67	271.09	289.39	271.10	278.76	271.06	264.88

Table 17
Amount of cost and reduction by each concrete mix design materials.

Materials	Cost[Won/m^3]							
	A company	B company	C company	D company	E company	F company	G company	Optimal
Cement	24,656	24,472	24,288	26,128	24,288	25,024	24,288	23,644
Coarse aggregate	23,300	23,125	23,275	23,275	23,500	23,925	22,700	23,325
Fine aggregate	21,800	20,875	22,400	22,400	22,400	22,550	21,875	20,200
Blast furnace slag	680	880	660	340	660	660	660	960
Fly ash	680	1,100	660	660	660	680	660	1,120
Water	1,600	1,760	1,600	1,600	1,600	1,600	1,600	1,540
Chemical admixture compound	610	584	528	536	528	544	528	570
Total	73,326	72,796	73,411	74,959	73,636	75,003	72,311	71,359

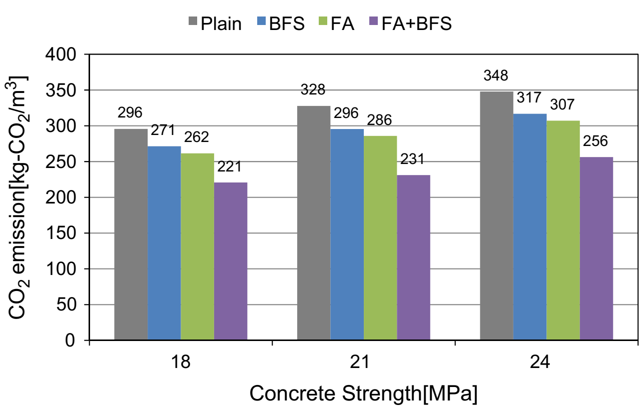


Fig. 1. CO_2 emission of concrete by kind of mixing admixture.

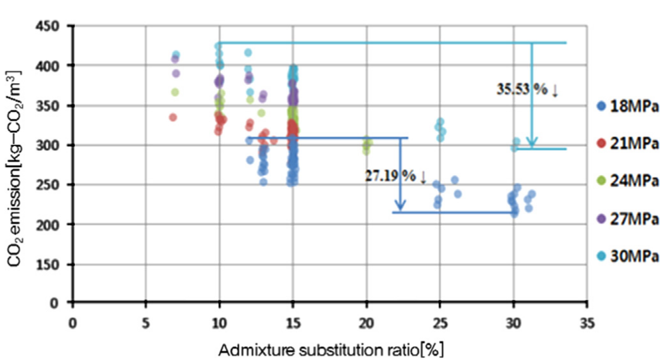


Fig. 2. Analysis of admixture mixing ratio and CO_2 emission.

amount, 264.81 kg-CO_2/m^3. Normal Portland cement emitted the maximum 268.1 kg-CO_2/m^3 for the actual mix design and 242.6 kg-CO_2/m^3 for the optimal design, contributing 92% of the total emission, and the fine coarse aggregate contributed the least to the total CO_2 emissions. Most of economic value per material

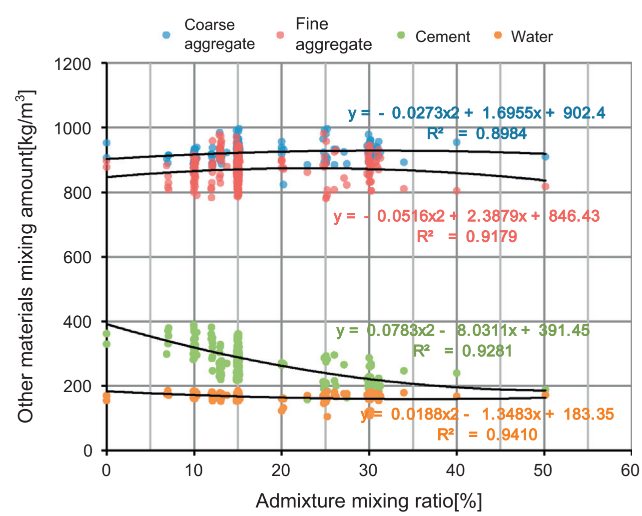


Fig. 3. Analysis of admixture mixing ratio and other materials mixing amount.

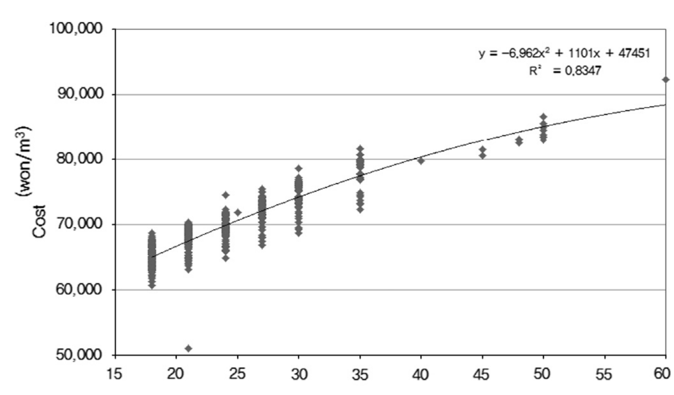


Fig. 4. Economic analysis based on the compressive strength of concrete.

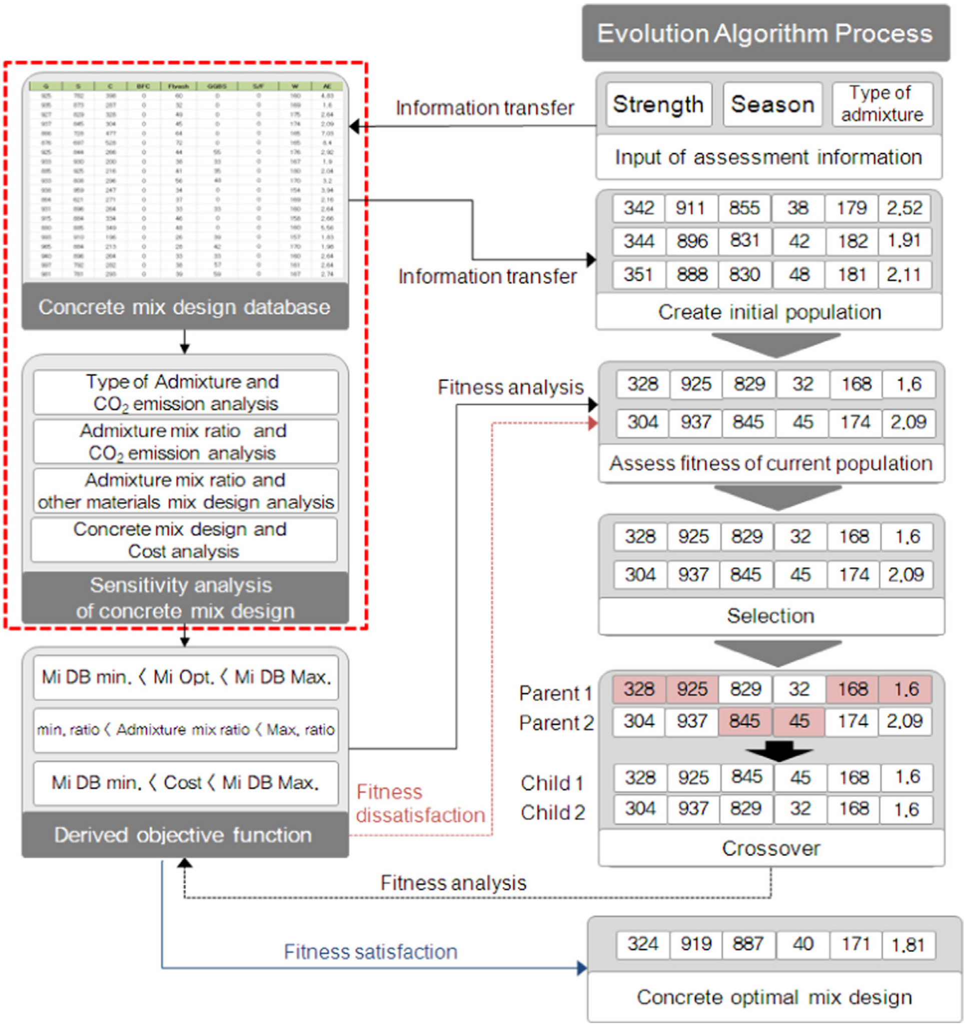


Fig. 5. Process to derive the optimal concrete mix design using evolutionary algorithm.

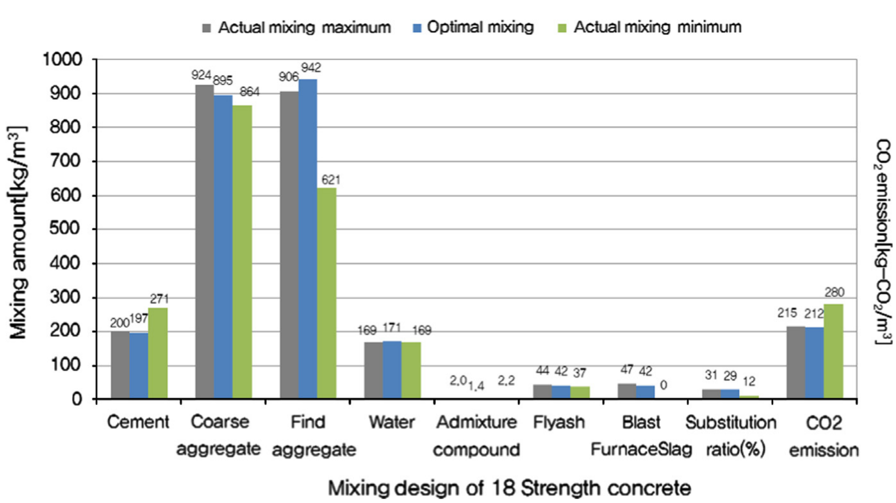


Fig. 6. Comparison of mixed amounts for each material between the optimal mix design and actual mix design.

was analyzed to consist of regular cement, coarse aggregate, and fine aggregate. Compared to Company F with the greatest economic value, the use of optimal mix design could make reduction up to about 5% per 1 m^3 of concrete. This is because the usage expensive regular cement was reduced while mix ratio of admixture with low production unit cost was increased. Mixing water and compounds were found to have little influence as shown in Table 17.



Fig. 7. Optimal design system for CO_2 emissions and cost in the life cycle of concrete. (a) Program main screen, (b) Basic Information Input Sheet, (c) Materials Stage Input Sheet, (d) Production Stage Input Sheet and (e) Evaluation Results Sheet.

6. Conclusions

This study used 'Low-carbon concrete mix design system' applied with evolution algorithm for the purpose of CO_2 emission reduction performance, and the following conclusion was drawn.

1 The low-carbon concrete mix design system was developed using a concrete mix design database established using Microsoft Visual Basic and EA.
2 About 800 concrete mix designs were investigated and formed into a database, through which the sensibility analyses for admixture type and CO_2 emission, admixture mix ratio and CO_2 emission, admixture mix ratio and other material mix amount, and material mix and economic value were conducted.
3 The evolution algorithm and target function found through sensibility analyses were combined to construct carbon reduction concrete optimal mix design search process satisfying material performance and environmental performance.
4 The suitability was reviewed for ranges of water binder (W/B) ratio and cement, coarse aggregate, fine aggregate, and water mix ratio, and as the result, a result similar to concrete mix design actually used was found.
5 As the result of case analysis of concrete mix design found through this evaluation system, 24 and 30 MPa with great concrete usage were reduced by 4 and 7%, respectively, when applied with optimal mix design instead of actual mix design, and economic value was reduced by 3 and 2%, respectively.
6 Additionally, the maximum, minimum, and average CO_2 emission of each standard actual mix design and the optimal CO_2 emission amount of the optimal mix design were analyzed. Compared with the maximum CO_2 emission of the actual mix, the maximum emission of the optimal mix was reduced by 17,

9, 24, 3, and 1% for 18, 24, 30, 45, and 48 MPa concrete, respectively.

7 Additionally, Also, the maximum, minimum, and average economic value of concrete actual mix design and economic value of optimal mix design were compared, and as the result, the optimal design saved economic value by about 5, 4, 5, 2, and 2%, respectively, for 18, 24, 30, 45, 48 MPa.

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